REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 29-08-2003	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE **Economics of Test Stand Renovation / Rebuilding**		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) David Harder		**5d. PROJECT NUMBER** **DARP**
		5e. TASK NUMBER **A205**
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**8. PERFORMING ORGANIZATION REPORT NUMBER** **AFRL-PR-ED-TP-2003-218**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S NUMBER(S) **AFRL-PR-ED-TP-2003-218**

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

For presentation at the AIAA Conference – Space Economics Forum – being held at Long Beach, CA, taking place 23-25 September 2003.

14. ABSTRACT

20031001 193

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A	14	**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

- Version as of 8 Sep 03
- incorporates changes/corrections identified on 3 Sep version

Economics of Test Stand 1D/2A Renovation/Re-building at Edwards AFB

David Harder, AFRL / PRFB

This paper provides some background information related to space infrastructure, rocket propulsion and rocket engine testing and discusses some economic considerations in the renovation/rebuilding of rocket engine Test Stands 1D and 2A at Edwards AFB CA. Various means used to minimize renovation/re-building costs and schedule are discussed as is the current state of the commercial rocket launch business.

Business Case Considerations

Rockets are used in a wide variety of systems applications, from tactical air-to-air missiles, to intercontinental ballistic missiles, to space launch vehicles. Rocket-propelled vehicles are high performance systems that place extreme demands on their propulsion subsystem. Consequently, a wide-variety of rocket sizes and types continue to find useful application, in contrast with other propulsion application areas, where propulsion systems have settled down into a relatively narrow range of propellant choices and power cycles.

The great variety of rocket propulsion systems demands an equal variety of rocket test facilities for a range of technical reasons. Solid rocket motor test facilities are generally horizontal firing by design. This has the advantage of being able to calculate thrust without having to subtract the changing weight of the motor as the propellant grain is consumed. Larger, segmented solid rocket motors, however, are often fired vertically because slumping characteristics of propellant grains and structural loading of inter-segment o-rings are issues that need verification before flight.

The preferred method for testing liquid rocket engines is vertical test firing, mainly to ensure timely and repeatable purging and draining of liquid propellants from injector domes during the critical startup and shutdown sequences. Sometimes, proper draining is accomplished by firing at a canted downward angle that is sufficient to ensure injector dome draining, especially when using kerosene fuel. Smaller engines are often tested horizontally, due to scaling factors associated with slug flow in small cavity sizes. Thrust chamber tests of large scale injectors have been done horizontally with hydrogen and oxygen fuel, aided by the volatile nature of these propellants.

Other characteristics make test stands application-specific. Run tank sizes must be large enough for sufficient duration, but small enough to minimize boiloff losses of cryogenics and to use pressurant gases efficiently. Run tanks must be vacuum jacketed when using liquid hydrogen fuel. Run lines must be roughly sized for an engine. Excessively small pipe diameters experience damaging water hammer during transients, turbine flowmeters that exceed their normal range, and pressure drops that exacerbate attempts to control pump inlet pressure. Too large of a run line diameter and turbine flowmeters fail to spin within their range of best accuracy, and propellant is wasted both dumping the excess line volume during and after test. A good rule of thumb is to keep run line diameters large enough to ensure line pressure drops are no more than 20% of run line liquid control valve delta-P, and small enough to allow the turbine flow meters to reach 80% of their calibrated maximum flow rate.

Thrust measurement systems are an important part of a test stand. They too experience limited range scaling. Engine thrust should be kept to no less than one-third of maximum thrust for best accuracy. Thrust measurement often includes side load measurement, especially for flight certification engines. These systems require engine-specific configurations that match the diameters and moment arms where the axial thrust and side-loads are taken out. Management of a fixed, repeatable configuration is especially important in order to make engine-to-engine comparisons over a long, 20-yr+ production run. Distortions in tube-type thrust chambers and injector flow patterns often cause variations in thrust vectors. It is important to understand the difference between geometric and actual thrust in order to program the flight control system that gimbals the engine during flight.

U.S. space launch vehicles are an outgrowth of the Inter-Continental Ballistic Missile (ICBM) programs of the 1960's. The Atlas, Delta, and Titan missiles were state-of-the-art, highly engineered products designed to performance goals rather than cost goals. Eventually, these missiles were converted into space launch vehicles, where reliability and cost became the two most significant issues for vehicle design.

When considering cost, reliability, and the range of payloads and orbits available, today's state-of-the-art space launch system is still an expendable vehicle. Low launch rates have historically stymied the business case for an entirely new vehicle design, due to high development costs and the reliability growth curve associated with a new system design. Space vehicle payload mass has been growing over the years, and it wasn't until the higher payload derivatives of the historic Atlas, Delta, and Titan vehicles were becoming increasingly contrived that a new, clean sheet system was envisioned that would allow a fresh start back to a high-margin, simple, reliable system. The business case for a new rocket system, which looked viable during the boom years of the mid-to late-1990's, looks poor with the benefit of hindsight, as the commercial capital investments have failed to pay off.

This lack of a business case for a new system development meant that every opportunity for savings in development costs must be explored. Development of the main engine of the booster is usually the highest-cost, highest-risk element of the program. Use of an existing test stand, with legacy back to the 1960's, ensured substantial savings of both cost and time.

These facts became apparent to the Air Force Evolved Expendable Launch Vehicle (EELV) program office, and in 1994 the EELV program office funded the activation of Test Stand 1A at Edwards AFB, CA. The objective was to prepare for the development of a new hydrogen booster engine for a new, clean sheet rocket vehicle. Test Stand 1A was built in 1955 for $11M. The additional propellant run tanks and handling systems added later brought the total cost to about $20M in 1955 dollars. The original combined cost of Test Stands 1C, 1D and 1E is estimated to be in the $33M range in 1963 dollars. Replacement costs are estimated to be in the $150M to $180M range for each of the stands, with construction requiring several years. In view of the costs and time required for replacement, renovation at 20-30% of replacement cost was very appealing.

By the later 1990's, the California Space and Technology Alliance (CSTA) felt that the state should attempt to promote itself as a leader in space technology. To quote from the situation summary of The California Space Strategic Plan 1999-2001 "An unprecedented surge in space technology development is creating a new space era: "The Space Services Age." Global space industry revenues are expected to grow from a 1997 total of $79 billion to $117 billion in 2001, a **48% increase in five years**. For the space telecommunications sector driving this expansion, a **97% growth rate is projected for the same five-year period**." With the benefit of 20/20 hindsight, these projections were extremely optimistic.

The US Air Force was also expressing a great deal of interest in Evolved Expendable Launch Vehicles (EELVs) and reusable launch vehicles (RLVs). The renovation of Test Stand 1A at Edwards had been recently completed and used for extensive testing of the Rocketdyne RS-68 LOX/hydrogen EELV engine, now used in the Delta IV launch vehicles.

The forecasted growth rates would in turn fuel demand for improved space infrastructure including the development and testing of boost vehicles. To further enhance the attractiveness of a renovation of Test Stand 1D, vehicle trades favored hydrocarbon as the most cost effective means for reusable launch vehicles due to the greater density and a higher thrust to weight ratio than hydrogen. Hydrocarbon fuels are relatively inexpensive in terms of initial purchase cost though some pose potential environmental challenges. LOX is more difficult to store and handle than are some of the hydrocarbon propellants, however as an oxidizer it has several advantages. It is not toxic and is readily available in the commercial market.

1D is one of three stands ideally suited to production acceptance testing of large, million-lbf class rocket engines. 1A is not well suited to hydrocarbon engine production testing, due to lack of engine gimbaling capability and lack of environmental controls for potential kerosene spillage. While these features can be added, the demands of a production program would eventually create schedule conflicts with the development testing on 2A.

$23.345M was received in FY 2001 to bring both of these stands back to a serviceable condition. An additional $10.398M was received in FY 2002 to complete the work. The Air Force Research Laboratory's Propulsion Directorate at Edwards had estimated that these amounts would be sufficient to do the needed renovation work.

Background/History

Test Stand 1D was designed in early 1962 along with Test Stands 1C and 1E by the Ralph M Parsons Co specifically to test the F-1 engine. Construction of all three stands took place in the 1963/64 time period. The pad, flamebucket and superstructure were constructed by the Army Corps of Engineers. The on stand equipment, (piping, tanks, valves, instrumentation, etc) were contracted to Rocketdyne Corp, now a part of

Boeing. This stand was originally constructed to test the Saturn F-1 engine, fueled by hydrocarbon (RP-1) with liquid oxygen (LOX) as the oxidizer. It was used for hundreds of tests for the F-1 engine until 1973, at which time it was mothballed. The low desert humidity limited any corrosion on metal components, though the sunlight and ultraviolet radiation were less kind to any exposed seals, gaskets and insulation.

Test Stand 1D was essentially renovated and updated to provide the same capability as was originally constructed. It was not substantially re-configured to provide additional capabilities. Retaining the original configuration allowed substantial cost savings relative to the cost to convert to another type of propellant. Additionally, many components (e.g., tanks, piping, pumps and valves) could potentially be re-used.

The re-use of numerous components and the quality of the original construction of the Test Stand 1D served to reduce the cost of renovation. Among these were the availability of the original drawings, re-use of ball valves, piping and tanks.

The original drawings and schematics for this facility were still available on microfiche. Had the drawings not been available, it is estimated that at least 2000 man hours at a cost of $500K would have been required to re-create them. More important than the cost savings were the time savings involved. Several months would have been required to take measurements, create the needed drawings, check them, etc.

Test Stand 1D utilized four large (18" diameter) ball valves as isolation valves in the run lines. These valves were designed specifically for the F-1 test application. The ball valves are a critical component from both a reliability and safety standpoint. The need for reliability is obvious, without reliable operation the stand cannot meet its intended function. Their reliability is also critical from a safety standpoint; in the event of engine fires or other accidents, the fuel and oxidizer supply can immediately be shut off. The valves were originally fabricated by Fisher-Vickery at a price of approximately $100K per valve (1963 dollars). Fisher-Vickery is no longer in existence, but Rocketdyne still services these valves. While it would be possible to find a contractor to design and fabricate a like item today, it would be extremely time consuming and expensive. The current alternative is the use of butterfly valves that are less reliable and do not provide as tight a seal. Acceptable butterfly valves are estimated to cost approximately $150K apiece. The ball valves were reconditioned with new seats and reinstalled on 1D at a cost of less than $15K per valve.

Test Stands 1C, 1D and 1E were designed conservatively to handle increased thrust levels anticipated as engines and propellants are improved as well as to withstand any hard engine starts that might occur with the F-1. This ensured the needed reliability to support time-critical testing required in the1960's. The inherent durability also served to mitigate renovation costs. Test Stand 1D was checked for corrosion and cracks to insure structural integrity. The superstructure was cleaned and repainted, the removal of the original lead-based paint being the most significant problem encountered.

1D incorporated a large amount of piping in various sizes. A significant quantity of the piping originally used was seamless, high pressure stainless steel pipe in varying sizes. While this type of piping is available in the commercial market today, it is quite expensive and lead times to obtain non-standard sizes are lengthy. Much of the larger diameter pipe (2 inches and greater) was reused. Smaller diameters could not be reused due to the difficulty in insuring that they could be adequately cleaned.

Test instrumentation was completely redone to bring it to current standards. Strip chart recorders were replaced with digital devices. Most of the cabling and wiring was replaced except for the portion that ran in tunnels, which was still in good condition.

Test Stand 2A was built in the early 1960's solely for the purpose of testing the F-1 thrust chamber assembly. It was used for this purpose until about 1965 when it was abandoned. During the late 1980's/early1990's the Idaho National Engineering Lab (INEL) did demolition work on the facility with the intention of redesigning it to test components for the Advanced Launch System (ALS) program. That program was terminated, but the design work proved valuable for the renovation program that was funded in 2001.

The intent both in INEL design and the current design was to build as much flexibility as possible into the facility. That was accomplished through the use of a common test stand infrastructure up to the point where it meets unique test article requirements. The common infrastructure has tanks and feed lines for various propellants along with LOX, nitrogen and helium. It also includes instrumentation runs to the test article interface point. The flexibility built into this facility will save future programs both schedule and money, in that the cost and time to configure it for different test articles is minimized.

A variety of innovative techniques were used in the renovation of test stand 2A to reduce costs and shorten the schedule. Since a great deal of high pressure piping is involved, the use of industry standards rather than military specification increased the available number of bidders who were familiar and able to bid on this type of work. Fixed price contracts which represented best value (price, past performance, capability) were utilized wherever possible. About three quarters of the contracts awarded were fixed price. Incentives were also used on contracts for specialized components which were on the critical path. Incentivized contracts were justified on the basis of the schedule/financial costs that would be incurred if these items were not delivered on time. They proved to be very effective.

A new liquid oxygen run tank was purchased for Test Stand 2A. Most of the other tanks required to provide the needed capability were salvaged from a variety of sources. The high pressure liquid hydrogen run tank was reused from the Space Shuttle Main Engine development program. It was determined to be more effective from a cost and schedule standpoint to cut and re-weld sections of salvaged thick-wall pipe than to obtain new pipe.

Two run tanks at Test Stand 2A provide propellant and oxidizer for the test firings. Each half of the tanks is a large forging (the tanks are 10 ft in diameter). The forgings, which are approximately 12 inches thick, are then manually welded together to make the complete tank. To obtain adequate strength, the edges of the forgings are beveled from the inside of each wall to the outside of the tank. The bevel is then filled with weld material so that the walls of the tank are solid. Replacement of these tanks with new items would cost an estimated $400K each. After cleaning and painting, the run tanks were pressure tested and determined to be sound for reuse.

Total savings attributable to reuse of existing components on Test Stand 2A were estimated to be between $7 and 8M. Additional saving in excess of $1M were realized through reuse of components on Test Stand 1D.

Both the renovation of Test Stand 1D and the re-build of Test Stand 2A benefited from the ready availability of skilled labor in the southern California area, particularly in the areas of pipefitting and welding. These skills are commonly utilized in refineries and other petrochemical facilities in this region.

Future Need For Test Facilities

The collapse of the space launch market over the last two to three years was not the optimistic scenario envisioned by the CSTA in their strategic plan. Currently there is excess capacity in space infrastructure, with little expected near-term growth in the commercial space market. In the August 25th issue of the Wall Street Journal, a front page article indicated that Boeing Co was taking $1.1B in charges related to reductions in revenue from the commercial satellite and rocket launch business. Of this amount, nearly $900M is associated with the Delta IV program, according to the article. The military launch situation is somewhat better, at least for the industry as a whole, though Boeing's military business is also impaired by the loss of seven launches to rival Lockheed as well as being barred from bidding for three additional launches. The article indicates that the revenue lost to Boeing as a result of losing these launches will approach another $1B. The US launch industry is dominated by a few large players; the loss of any one firm leaves a less capable technical base. Clearly this is a difficult environment in the commercial space arena and offers little incentive for the development of new components and engines. Nevertheless, given the long lead time for the development of new engines, it is expected that the military will continue to invest at some level to insure that capabilities are available to meet future requirements.

The renovation of Test Stand 1D and the re-build of Test Stand 2A potentially represents a significant subsidy for both future military projects and commercial developments. Commercial space development will continue to be constrained by profit considerations. Risk will be mitigated through the use of proven technology. Military applications, not driven by the profit motive are still constrained by limited funding and schedules. As rocket engine technologies evolve, testing requirements and methods will also evolve. It is doubtful that the need for actual hot fire testing will ever be totally eliminated.

Acknowledgements: I would like to thank Robert Drake, Eric Schmitt, Sean Kenney and Bill Lawrence for their contributions to this paper. They provided a great deal of insight and information. I also want to thank Jim Bowmann who provided historical information concerning costs and construction ~~construction~~ of Test Stands 1D and 2A. for the space program